Design of a Compact Power Conditioning Unit for use with an Explosively Driven High Power Microwave System

J. Korn, A. Neuber, A. Young, C. Davis, M. Kristiansen
Center for Pulsed Power and Power Electronics, Texas Tech University
MS 43102, Lubbock, Texas, 79409-3102, USA

L.L. Altgilbers
U.S. Army, SMDC, Huntsville, Alabama

Abstract

The generation of high power microwaves using explosively driven pulsed power is of particular interest to the defense community. The high energy density of explosives provides the opportunity to design pulsed power systems which occupy significantly less volume, yet provide the same output power, as traditional methods of High Power Microwave (HPM) production. Utilizing a Flux Compression Generator (FCG) as explosive driver necessitates introducing an intermediate Power Conditioning System (PCS) that addresses the typical impedance mismatch between FCG and HPM source. The presented PCS is composed of an energy storage inductor, an opening fuse switch and a self-break peaking gap all of which needed to fit within an envelope of 15 cm diameter. Currents in the tens of kilo-amperes and voltages in the hundreds of kilo-volts have to be handled by the PCS. The design of the system, which takes up less than 11 liters of volume, as well its performance into a 20 Ω resistive load (used to approximate the operating impedance of certain HPM sources) is presented. Approximately 6 GW of electrical peak power was delivered to the load.

I. INTRODUCTION

If a single pulse of power is desired to drive a load, and the available volume is significantly limited, explosive power is a sensible choice for electromagnetic pulse power. The chemical energy stored in high explosives can reach upwards of 8 GJ/m^3, compared to capacitors, which can only reach about 1 MJ/m^3 of electrically stored energy. For practical applications, the efficiency of converting the chemical into electrical energy needs to be considered, however, even with poor conversion efficiency, the energy density of explosively driven systems will remain at least an order of magnitude greater than a capacitor driven system. Discharge time for high explosives is on the order of microseconds, which is reasonable, but may require some conditioning on the electrical output side to become comparable to a fast capacitive discharge.

This manuscript details power conditioning experiments with a dual-stage Helical Flux Compression Generator (HFCG) with flux trapping. A major limitation of the HFCG is that the load must possess low impedance or resistance characteristics in order to maximize generator performance [1]. One approach is to provide a low impedance path initially for the build-up of energy and then use an opening switch to divert the energy/current to a higher impedance load.

There are two popular methods of providing the current interruption necessary to provide effective transfer of energy to an HPM load. One is an explosively formed fuse, which uses explosives to deform the fuse conductors and disrupt current flow. The second is an electro-explosive fuse (exploding wire fuse), which uses I^2R heating in the fuse conductors to vaporize the wire. The experimental study of compact exploding wire fuses with a non-explosive FCG simulator has been used to optimize fuse designs for use in an explosive system [2]. Once optimized, the design is then integrated into the explosively driven experimental setup and tested. Presented here are data and waveforms from these integration experiments, where results are used to predict the behavior of the HFCG-Power Conditioning System (PCS) when connected to a triode vircator.

EXPERIMENTAL OVERVIEW

The overall setup has four main components: the HFCG, PCS, diagnostics and load, as shown below in Fig.1 (no diagnostics shown).

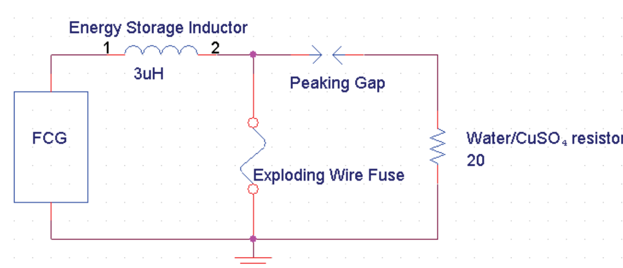

Figure 1. Schematic Representation of Experiment

A. HFCG

As mentioned previously, the HFCG used in these experiments consists of two cascaded stages which are coupled to one another through the use of a dynamic transformer. The energy supply used to "seed" the HFCG with electrical energy is also coupled to the first cascade through a dynamic transformer. The function of the first

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2009	**N/A**	**-**

4. TITLE AND SUBTITLE
Design of a Compact Power Conditioning Unit for use with an Explosively Driven High Power Microwave System

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Pulsed Power and Power Electronics, Texas Tech University MS 43102, Lubbock, Texas, 79409-3102, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
The generation of high power microwaves using explosively driven pulsed power is of particular interest to the defense community. The high energy density of explosives provides the opportunity to design pulsed power systems which occupy significantly less volume, yet provide the same output power, as traditional methods of High Power Microwave (HPM) production. Utilizing a Flux Compression Generator (FCG) as explosive driver necessitates introducing an intermediate Power Conditioning System (PCS) that addresses the typical impedance mismatch between FCG and HPM source. The presented PCS is composed of an energy storage inductor, an opening fuse switch and a self-break peaking gap all of which needed to fit within an envelope of 15 cm diameter. Currents in the tens of kilo-amperes and voltages in the hundreds of kilo-volts have to be handled by the PCS. The design of the system, which takes up less than 11 liters of volume, as well its performance into a 20 Ù resistive load (used to approximate the operating impedance of certain HPM sources) is presented. Approximately 6 GW of electrical peak power was delivered to the load.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

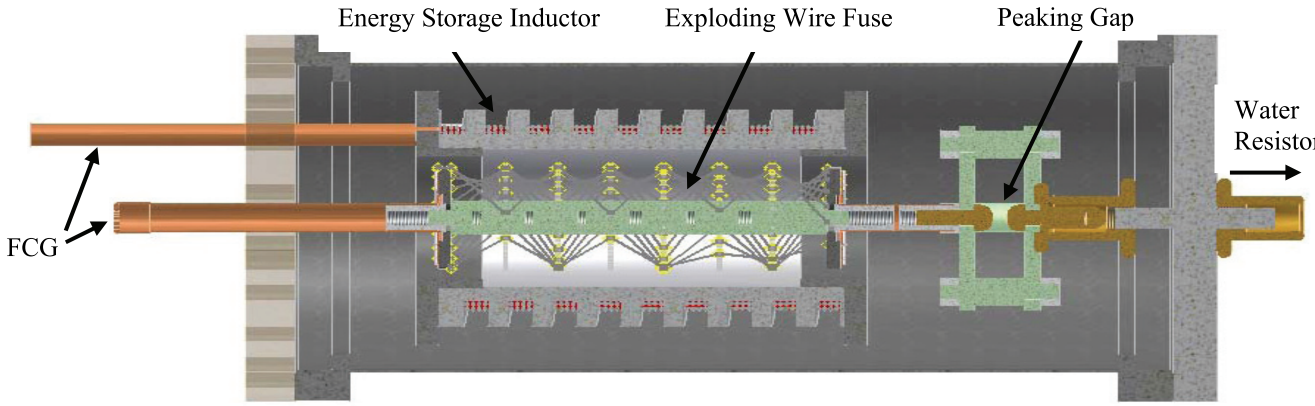

Figure 2. Power Conditioning Components

cascade (referred to as the booster stage) is to provide the main energy amplification of the generator. This can be seen by comparing the initial inductance of the booster stage helix to its load (~85 μH and 450 nH, respectively) [10]. The second cascade (referred to as the peaking stage) shortens the relatively long pulse of the first cascade (~30 μs to ~10 μs), and also provides a voltage step-up (through the dynamic transformer), allowing energy to be transferred into a load with an inductance value in the microhenries [1].

B. Power Conditioning System

The PCS depicted in Fig. 2 consists of three main components: the energy storage inductor, fuse opening switch and peaking gap. The fuse opening switch is coupled in series with the inductor. The inductor that is presented here replaces one that is over twice its length [3]. The previous inductor was wound with nine AWG-12 Litz wires connected in parallel. These wires were wound flat (overall rectangular cross-section) for 12 turns, which unnecessarily increased the overall length to 35 cm. The new design uses eight AWG-12 Litz wires connected in parallel and wound onto an 89 mm diameter PVC mandrel. The wires were stacked (square cross-section), which resulted in a decreased coil pitch. The increased turn density enabled the inductor to attain a similar inductance value to the original design, ~2.7 μH and ~3.2 μH respectively, with only seven turns and an overall length of ~15 cm. When measured with an LCR meter at 400 kHz (the approximate frequency of the HFCG output pulse), the inductor showed a resistance of 3.5 mΩ, which is a significant reduction over the 25 mΩ of the previous design. The length of the inductor is slightly larger than the length of the electro-explosive fuse that is contained within its volume, optimizing the available space.

The fuse is fabricated by winding silver wire with a diameter of 127 μm in a helical pattern between eight polycarbonate gear plates. The fuse used in the data shown in this manuscript was wound with 14 silver wires, for an overall conductor cross-section of 0.177 mm^2. As discussed earlier, the fuse has a total length just under 15 cm, while the overall length of the fuse wire was ~30 cm [3].

Due to the high voltage induced during PCS operation, effective high voltage design was necessary to prevent electrical breakdown between PCS components. One method of lowering the probability of voltage breakdown was to use SF_6 as an insulating gas. The breakdown field strength of a uniform gap in air and SF_6 is 173 kV/cm and 570 kV/cm, respectively, when pressurized to ~ 6.4bar [4]. The SF_6 also attaches with electrons produced during vaporization of the fuse wire, inhibiting re-strike [5]. Therefore, the PCS was placed inside a 15 cm diameter PVC tube and pressurized with SF_6 to ~6.9 bar. In addition, the inductor coil was wound into threads machined into on the PVC mandrel (see Fig. 2), where the added insulation lowered the potential of turn to turn breakdown.

To isolate the HFCG and PCS from the water resistor dummy load before fuse vaporization, a self-break peaking gap was employed. The peaking gap is composed of brass electrodes set at a distance of 2 mm from one another, for an estimated self-break voltage of ~120 kV in 6.9 bar of SF6.

C. Water Resistor Dummy Load

A water resistor was used to approximate the operating impedance of the triode vircator used in HPM generation experiments [3]. It is important to note that the impedance of the triode vircator varies with time and will eventually collapse when the AK gap shorts out. However, 20 Ω gives a good approximation to those seen in experiments and literature [6]. An estimate of the peak voltage expected at the load, ~300 kV for this design, was used to calculate the dimensions of the water resistor.

$$h=V_{peak}/E_{field} \quad (1)$$

The suggested electric field in a water resistor should not exceed 15 kV/cm [7] (E_{field} in Equation 1). The calculated height, or length, of the resistor using Equation 1 (V_{peak} = 300 kV, E_{field} = 15 kV/cm) was 200 mm. $CuSO_4$ was mixed with de-ionized water to form a electrolytic solution with a resistance of 19.5 Ω. Energy dissipation in a water resistor takes place in the heating of the aqueous-electrolytic solution [8]. As a consequence, air can accumulate over time and change the resistance. To combat this, a bleeder valve was incorporated into the design to extract air from the resistor volume. As can be seen in Fig. 3, the water resistor was placed within a stainless steel ConFlat tube, which also served as the return electrical connection to the rest of the circuit during experiments. To prevent surface flashover between the high voltage feed-through and ConFlat tube, the volume was pressurized with 3.4 bar of SF_6.

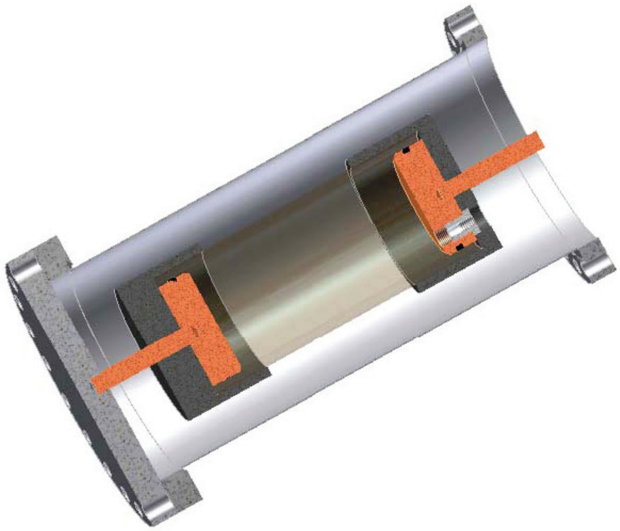

Figure 3. Water Resistor Design in ConFlat Tube

EXPERIMENTAL RESULTS

About 15 generators were fired into the IES inductors without a fuse. Two generators were fired into the compact power conditioning system, including fuse and dummy load. The current magnitude at the time of crowbar is used to calculate the seed energy through $^1/_2 * L_{seed} * I_{seed}^2$ [9]. From the waveform, the current magnitude at the time of crowbar is ~7.4 kA, giving a seed energy of ~180 J. The measured current maximum was 40 kA. The total energy stored in the energy storage inductor was 2.2 kJ. The energy amplification is ~ 12. Note that the current monitor had about 200 ns rise time such that the peak of ~70 kA (seen in Fig. 5) is not due to a real current amplitude but rather due to noise from the fuse opening and peaking gap closing.

The waveform in Fig. 5 shows that the fuse was somewhat overdriven, since the fuse opened ~8 µs into the second stage, which has a 10 µs run-time. The peak dI/dt of the HFCG output was about 9.5 kA/ µs, which is limited by the fuse becoming more resistive with increasing current action integral. The energy stored in the inductor is about 2.2 kJ at its maximum with roughly 0.9 kJ (25 kA) remaining after fuse opening. Of this difference (1.3 kJ), the dummy load dissipated about 1.1 kJ, derived from $\int V^2/R dt$ of the voltage waveform in Fig. 6. The maximum voltage across the load was measured to be about ~330 kV.

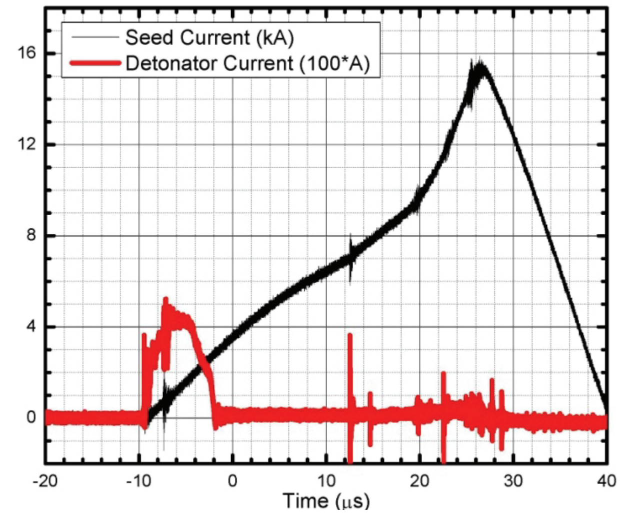

Figure 4. Seeding Current and Detonator Waveforms

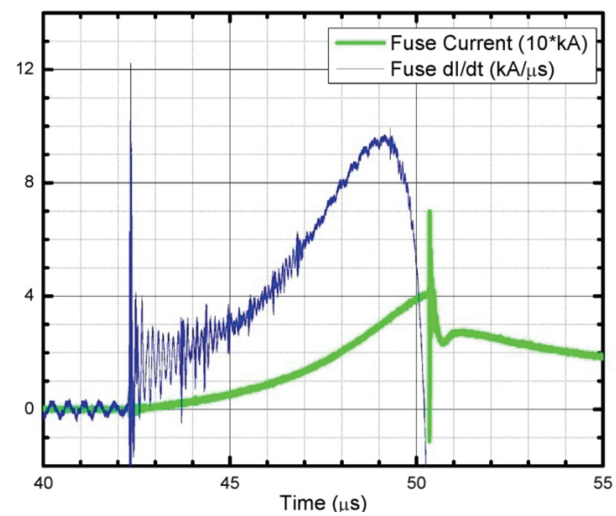

Figure 5. Current Waveforms into 2.7 µH Load

The results from the second shot were similar, however, with less re-strike on the fuse, as the FCG performance was compromised by the second stage switching in too early (seen by the negative current value before the quasi-exponential rise in Fig. 7). The maximum fuse current reached the value of approximately 38 kA. Although this current amplitude is comparable to the previous shot, the voltage across the inductor dropped significantly to 280 kV as shown in Fig. 8, probably a consequence of the fuse being driven to vaporization on a longer time scale.

The current magnitude at the time of crowbar is about 7.4 kA, giving a seed energy of 178 J. The measured current maximum was 38 kA from Fig. 7, the total energy in the storage inductor was 2 kJ, with about 0.8 kJ dissipated in the load. The energy amplification is ~11. Note that this is a conservative estimate since the actual amplification factor is somewhat higher due to the few 100 nH inductance in the interconnections that add to the energy storage inductor, which has an inductance of 2.7 µH by itself.

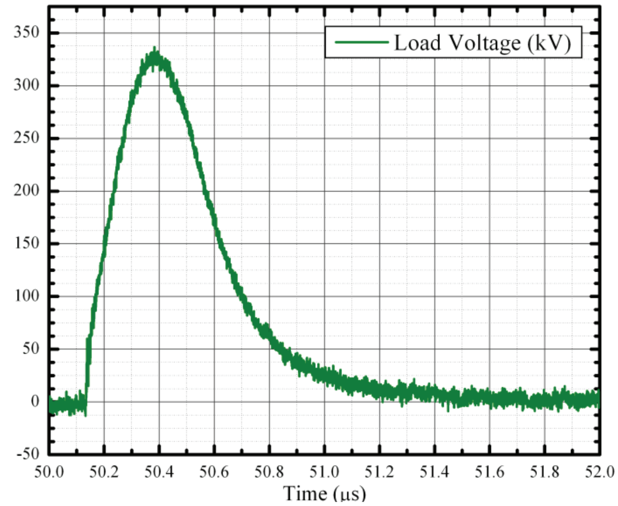

Figure 6. Load Voltage Waveform

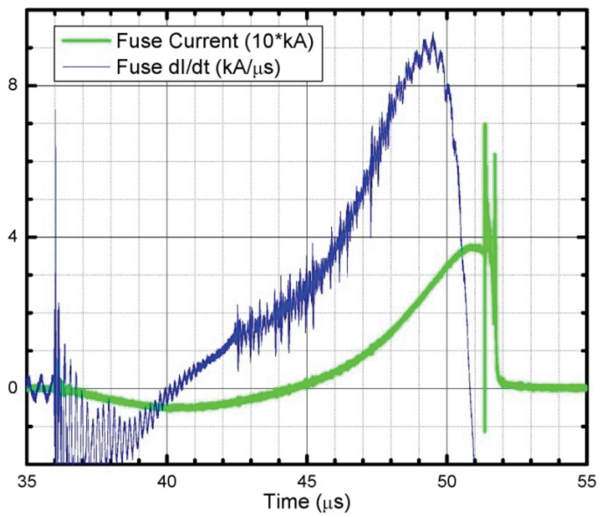

Figure 7. Current Waveforms into 2.7 µH Load

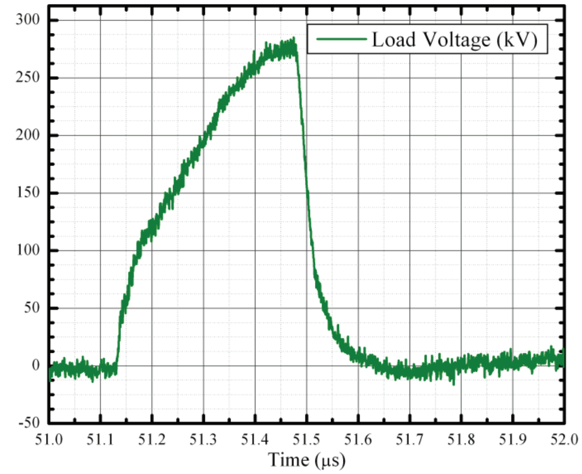

Figure 8. Load Voltage Waveform

SUMMARY

The compact power conditioning system and generator was capable of producing a 330 kV pulse, which was almost 3 times as much as previously achieved. One method to improving this system was to add wires in parallel for the energy storage inductor to lower its resistance. Further improvement is expected with shortening the interconnections of ~1 m in length between seed source - FCG - load in an all-integrated system as well as optimizing the components to work together more efficiently.

REFERENCES

[1] A.A. Neuber, Explosively Driven Pulsed Power: Helical Magnetic Flux Compression Generators, Springer Verlag, Heidelberg, 2005.

[2] C. Davis, et al., "Power Conditioning Optimization for a Flux Compression Generator Using a Non-Explosive Testing System," 2009 International Conference on Pulsed Power and Plasma Science, (Washington DC), June 29-July2, 2009, *these proceedings*

[3] A. Young, A. Neuber, M. Elsayed, J. Walter, J. Dickens, M. Kristiansen, L.L. Altgilbers, "Stand-Alone, FCG Based High Power Microwave Source," 2009 International Conference on Pulsed Power and Plasma Science, June 2009, *these proceedings.*

[4] E. Kuffel, W.S. Zaengl and J. Kuffel, High Voltage Engineering: Fundamentals. Burlington, MA: Elsevier, 2006, pp. 281-348.

[5] D. McCauley, et al., "Electro-Explosive Fuse Optimization for Helical Flux Compression Generators Using a Non-Explosive Test Bed," 2007 International Conference on Pulsed Power and Plasma Science, (Albuquerque, NM), June 17-22, 2007.

[6] J.Benford, J. Swegle, E. Schamiloglu, High Power Microwaves 2nd Ed. 2007

[7] W. Mosch, Electrotechnik 9, 1955, pp. 214.

[8] A.E. Bishop, G.D. Edmonds, "Electrolytic Resistors in Plasma Physics Research," Journal of Nuclear Energy Pt. C, 1965, Vol. 7, pp. 423-426.

[9] A. Young, et al., "Fuse and Load Testing with Mid-Sized, High Energy Density Flux Compression Generators," 2007 International Conference on Pulsed Power and Plasma Science, (Albuquerque, NM), June 17-22, 2007.

[10] T. Holt, A. Young, A. Neuber, M. Kristiansen, "A Fabrication Method for a Mid-Sized, High Energy Density, Flux Compression Generator", Proc. of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, pp. 281-286, September 2006.